AD-A106 259   HYDROLOGIC ENGINEERING CENTER DAVIS CA   F/G 13/2
OPERATIONAL SIMULATION OF A RESERVOIR SYSTEM WITH PUMPED STORAG--ETC(U)
FEB 79 G F MCMAHON, V R BONNER, B S EICHERT
UNCLASSIFIED HEC-TP-60 NL

1 OF 1
AD A
106259

END
DATE
FILMED
11-81
DTIC

AD A106259

TECHNICAL PAPER NO. 60

(12)

OPERATIONAL SIMULATION OF A RESERVOIR SYSTEM WITH PUMPED STORAGE

by

GEORGE F. McMAHON
Vernon R. ~~VERN~~ BONNER
BILL S. EICHERT

Scott

(11) Feb 77

(14) HEC-TP 60

(12) 33

HEC

THE HYDROLOGIC ENGINEERING CENTER
•research
•training
•application

CORPS OF ENGINEERS
U. S. ARMY

Papers in this series have resulted from technical activities of The Hydrologic Engineering Center. Versions of some of these have been published in technical journals or in conference proceedings. The purpose of this series is to make the information available for use in the Center's training program and for distribution within the Corps of Engineers.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER Technical Paper No. 60	2. GOVT ACCESSION NO. AD-A106259	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) OPERATIONAL SIMULATION OF A RESERVOIR SYSTEM WITH PUMPED STORAGE		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) George F. McMahon, Vern Bonner and Bill S. Eichert		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Corps of Engineers The Hydrologic Engineering Center 609 Second Street, Davis, CA 95616		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE February 1979 13. NUMBER OF PAGES 32
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution of this publication is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Presented at Water Systems 79 Conference-American Society of Civil Engineers, Houston, Texas

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Hydroelectric power generation; Mathematical models; Pumped storage; Reservoir operation; Reservoirs; Water resources.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Richard B. Russell Dam and Lake Project is presently under construction and is being placed in tandem between Hartwell and Clark Hill, two existing multipurpose hydropower plants on the Savannah River. System operational simulations were performed in support of a feasibility study for the installation of pump turbines at Russell, using a version of the Corps of Engineers HEC-5C computer program modified for system power and pumped storage. Information developed from the simulations include system hydropower (Continued)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20 (Continued)

production, pumping energy requirements, daily reservoir pool fluctuations, and reservoir elevation statistics. This information was useful in judging the effects of the addition of pumped storage on system hydropower production and reservoir recreation useability, as well as in ascertaining efficient system operational methods.

OPERATIONAL SIMULATION OF A RESERVOIR SYSTEM WITH PUMPED STORAGE

By George F. McMahon[1], A. M., A.S.C.E., Vernon R. Bonner[2], M., A.S.C.E., Bill S. Eichert[3], M., A.S.C.E.

Introduction

Reservoir operation for multiple subject purposes often conflicts with optimal operation for individual purposes. This paper describes an operational simulation used to evaluate the effects of the addition of pumped storage on hydropower production and recreation useability of a reservoir system. The operational simulation is in support of a study to determine the feasibility of installing pump-turbines at the Richard B. Russell Dam and Lake project, presently under construction and currently authorized for conventional hydropower, flood control, and recreation. The pumped-storage feasibility study addresses the recreational, environmental, hydropower, water supply, and economic impacts of pumped storage and conventional hydropower production at Russell on Corps of Engineer's dams on the Savannah River.

---

[1]Hydraulic Engineer, U.S. Army Corps of Engineers, Savannah District, Savannah, Georgia.

[2]Hydraulic Engineer, U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, California.

[3]Director, U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, California.

Presented at Water Systems 79 Conference - American Society of Civil Engineers, Houston, Texas, February 1979.

These dams are Hartwell (in operation since 1962), Richard B. Russell, and Clark Hill (in operation since 1952). The purpose of the feasibility study was to investigate the need for and feasibility of adding pump turbines to the Richard B. Russell dam. Since the most feasible plan based on economic, environmental, and social considerations called for 300 MW of additional peaking capacity at Russell, the operational simulation was performed using the authorized 300 MW of conventional capacity in addition to the 300 MW pumped-storage capacity. The simulation was performed to furnish better information on hydropower production and reservoir pool elevations and fluctuations than had previously been available. Specific data furnished by the simulation for the Savannah River dams included hydropower production using different operational requirements with and without pumped storage at Russell, within-day reservoir pool fluctuations, and reservoir pool elevation-duration data.

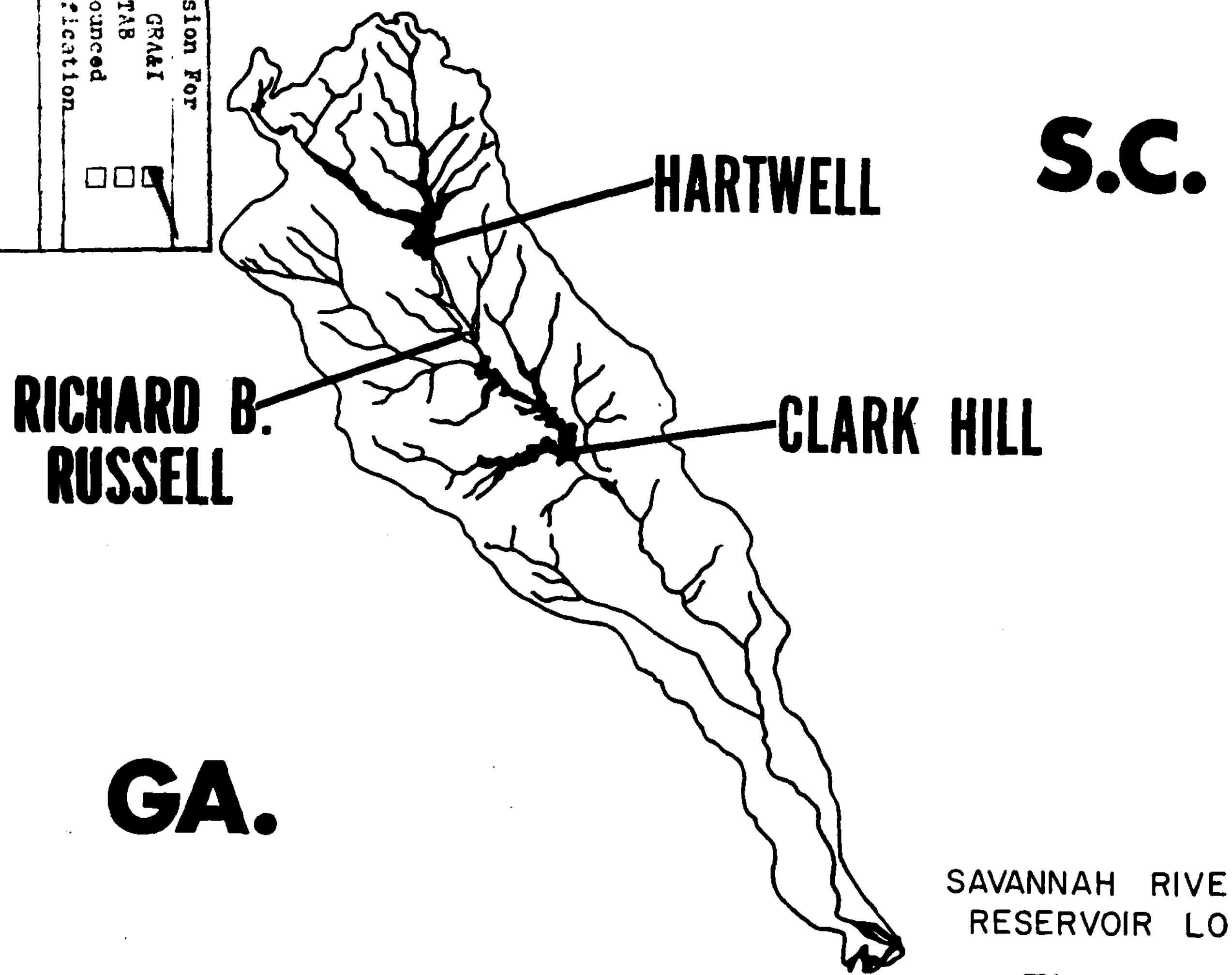
Hydropower production was simulated in order to determine system energy output with and without pumped storage at Richard B. Russell, and to determine pumping requirements. This information was useful in ascertaining operational methods for the system which will decrease primary energy shortages, dump energy, and pumping energy requirements, while maintaining a balance of system storage and meeting all other system requirements. This study was not conducted to determine system reliability, but only to develop operational information from expected system requirements. Three general conditions simulated were system

operation without pumped storage at Russell, system operation with pumped storage at Russell, and system operation with pumped storage and additional at-site requirements at Russell. The last was performed to insure full or even slight over-utilization of Russell in the system for purposes of determining maximum pool fluctuations in Russell and Clark Hill reservoirs.

Since Richard B. Russell with pumped storage will have more than the combined generating capacity of Clark Hill and Hartwell with only about 1/10 of their respective conservation storages, the effect of the addition of pumped storage on reservoir pool fluctuations and subsequent recreation useability of all three reservoirs merited particular study. Severe pool fluctuations can adversely affect recreation due to reservoir shoreline erosion and increased difficulty of maintaining recreation areas. It was felt that fluctuations of more than 2 feet per day would be unacceptable from a recreation standpoint. The operational simulation yielded results from which judgements concerning recreation useability could be incorporated into the feasibility study.

Description of the Savannah River System

For the purposes of the study, the Savannah River system consists of three Corps of Engineers hydropower plants located in tandem on the Savannah River. A general location plan of the three reservoirs is shown in Figure 1.



SAVANNAH RIVER SYSTEM
RESERVOIR LOCATION

FIGURE 1

Hartwell, the most upstream project, is located on the Savannah River approximately 7 miles below the confluence of the Tugaloo and Seneca Rivers, about 7 miles east of Hartwell, Georgia. The plant was placed in operation in 1962 as a 264-MW peaking plant, operating at an average head of 180 feet (55m). The lake has an annual visitor attendance of more than 7 million and ranks amoung the top ten most popular Corps of Engineers lakes in the United States. Storage demands on Hartwell are limited to peaking power production. The drainage area above Hartwell is 2,088 square miles and the lake has nearly 1.5 million acre feet (1.85×10^9 m^3) of power storage.

The Richard B. Russell (formerly Trotters Shoals) Dam and Lake project is presently under construction and is located on the Savannah River 30 miles below Hartwell near Calhoun Falls, South Carolina. The local drainage area between Hartwell and Russell is 812 square miles. Russell is currently authorized as a 300-MW peaking plant, although feasibility studies for inclusion of pumped storage are presently underway as previously discussed. If pumped storage were authorized at Russell, pump turbines will be installed with an additional capacity of 300 MW. Average generation and pumping head will be approximately 145 feet (44m) with the upper end of Clark Hill Lake serving as the pumping forebay. Storage demands at Russell will be limited to peaking power production with either conventional or pumped-storage operation, although there is much less power storage (126,800 açre-feet or $1.56 \times 10^8 m^3$) than at either Hartwell or Clark Hill. The plant will be operated on a daily cycle with pumped storage.

Clark Hill Lake is located on the Savannah River downstream of Russell approximately 22 miles above Augusta, Georgia. Clark Hill was placed in operation in 1952 for peaking power, but is also required to maintain average daily flows above a certain level for navigation on the Savannah River below Augusta. Installed capacity at Clark Hill is 280 MW conventional at an average head of 146 feet (45m). Local drainage area between Russell and Clark Hill is 3,244 square miles, and the lake has over 1 million acre-feet ($1.23 \times 10^9 m^3$) of power storage. Clark Hill is also one of the ten most popular Corps of Engineers lakes, with an average annual visitation of 5 million. Since the lake forms the potential pumping forebay for the Russell project, pumping at Russell will impact reservoir pool fluctuations at Clark Hill.

Previous Studies

There have been many studies of other reservoir systems for recreation usability and hydropower production, although, to the best of the writers' knowledge, there have been no operational simulations which satisfy both objectives and include system power and pumped-storage operation. Studies for Georgia Power Company's Wallace Dam[1] have some features in common with the Richard B. Russell project. Wallace Dam, a low-head project in the headwaters of Georgia Powers' Lake Sinclair, was studied for conventional and pumped-storage feasibility. Wallace Dam, like Russell, has a small annual power pool fluctuation (2 feet versus 5 feet for Russell). Wallace Dam also has a

relatively small amount of power storage, and 324-MW of combined pump and conventional generation capacity. Estimates were made in the Wallace Dam study of normal daily reservoir drawdown, normal reservoir elevation, and average annual energy production, although there is no discussion of these estimates being based on an operational simulation.

Probably the most extensive power pondage and water surface fluctuation studies have been performed for reservoir systems in the Pacific Northwest[2,3]. These studies include hourly routings for selected 1-week periods in various seasonal periods defined by flow conditions and generation requirements. Simulations were conducted for 15 reservoirs operated to meet system power demands. Water surface fluctuations were evaluated using routing methods available in the SSARR (Streamflow Synthesis and Reservoir Regulation) model or the SOCH (Simulation of Open-Channel Hydraulics) program. These studies did not specifically simulate pool fluctuations at pumped-storage plants, how ever. Inventory studies of pumped storage sites have been performed in the Pacific Northwest[4], in which the effects of daily/weekly draw down on reservoir recreation were addressed, but not evaluated.

Several other hydropower studies have been conducted in the Northeast[5], but none include operational simulations for system energy and pumped storage.

In addition to methods developed in support of the studies dis cussed above, other methods have been developed to model reservoir systems[6] and reservoir operation for recreation useability[7]. However, these are primarily optimization models and do not provide for pumped storage or system energy.

Description of the Model.

The operational simulation for the Savannah River system was per formed using a version of the computer program HEC-5C (Simulation of Flood Control and Conservation Systems) originally developed and later modified by the U.S. Army Corps of Engineers Hydrologic Engineering Center for pumped-storage and system energy applications. The program simulates sequential operation of a system of reservoirs in any configuration for historic or synthetic inflow periods. The program was developed to assist in planning studies for evaluating proposed reservoirs in a system and to assist in allocating storage for each project in the system. The original program did not have system energy or pumped storage capabilities, although these were developed and added to the program for the operational simulation. Specifically the program may be used to determine:

(1) Flood control and conservation storage requirements for each reservoir in the system.

(2) The influence of a system of reservoirs on the spatial and temporal distribution of runoff in a basin.

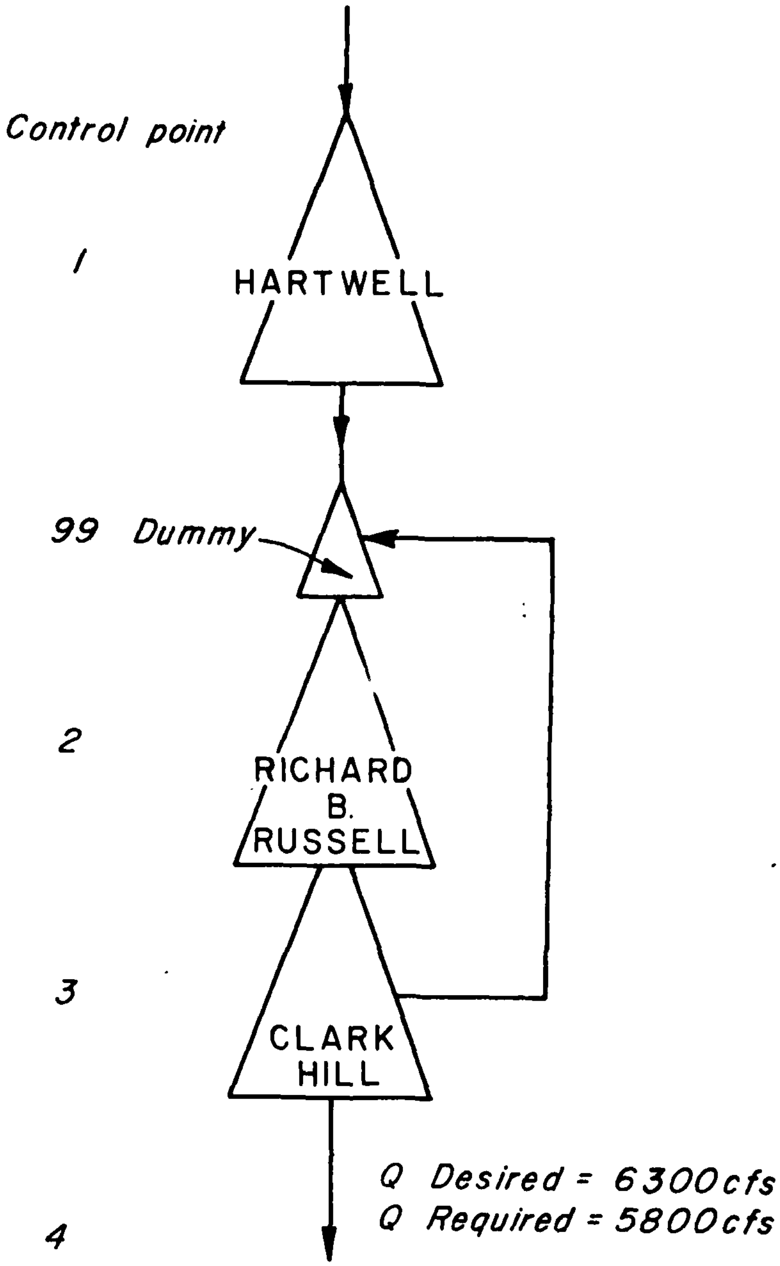
(3) The evaluation of operational criteria for flood control and conservation (including conventional and pumped storage hydropower) for a system of reservoirs operating individually or as a system.

(4) The epected annual flood damages, systems costs, power benefits, and system benefits for flood damage reduction.

Reservoirs can be operated to meet requirements at any number of downstream control points. Upstream tandem reservoirs may not be operated directly for control points below a downstream tandem reservoir, although HEC-5C considers upstream system storage when making releases from the downstream reservoir.

HEC-5C was applied in this study to evaluate the effects of operation to meet hydropower and navigation requirements on reservoir elevations and fluctuations. The routing interval used for the simulation was 24 hours, although any integral number of hours can be used.

Pumped storage was added to the program by using a dummy reservoir with no storage to define the pumping of water from the lower reservoir to the upper reservoir. Power data input for the dummy location is applicable to pumping, rather than generating. These data include pumping capacity, efficiency, penstock capacity and available pumping energy. Figure 2 shows the model arrangement for the Savannah River system, including the dummy reservoir.



MODEL ARRANGEMENT
SAVANNAH RIVER SYSTEM

FIGURE 2

The initial estimate of pumpback discharge is based on the available energy defined by input. The tailwater elevation is based on the higher of the base level elevation or the lower reservoir level. The upper reservoir elevation is used with the tailwater elevation in computing the head. Two feet of head loss are added by the program for all hydraulic losses. The computed discharge is checked to ensure it does not exceed the penstock capacity. Checks are also made to ensure there is sufficient water in the lower reservoir and that the upper reservoir is not filled above top of power pool elevation.

System energy capabilities were also added to HEC-5C. System energy requirements are met by drawing from system storage within daily plant factor constraints specified for each site. At the start of each time period, the modified routine for system energy determines what releases are required to provide the total energy while keeping the power reservoirs at the same level (same fraction of available power storage). The allocation routine also considers the minimum flow and power requirements of individual projects and pumpback discharges. The release allocation is then used by the program for that time period. If there are no other constraints on the system to change the releases, all system projects will be drawn down together to meet the total energy requirement. For flood control operations, current releases can be constrained by current requirements and forecasted inflows. Forecasting constraints are not used in determining conservation releases.

Within the 24-hour time interval used in the simulation, the program used average daily data and provided end-of-day reservoir storage and elevation. To provide an estimate of pool fluctuations between the pumping and generating cycle, the program was modified to estimate a mid-day storage and elevation. All pumping was assumed to occur during the first half of the day and all generating was assumed to occur during the second half of the day. This does not imply there were 12 hours of generating energy required or pumping energy available, since generating and pumping are limited by input plant factor constraints. The separation into two periods reflects the fact that pumping and generating do not occur simultaneously. Inflows and evaporation were distributed to the two half-day periods. The two daily elevations and their differences were written to a scratch file for later processing.

A detailed description of the HEC-5C model including input-output requirements and options can be found in the users' manual[8].

Model Input and Data Managment

SELECTION OF ROUTING PERIOD. The base period selected for simulation included water years 1951-1961, due to the availability of unregulated stream flow data at gages near all three plants on the Savannah River, and to this period including the period of maximum drawdown for Hartwell and Clark Hill. Clark Hill became operational in 1952 and Hartwell became operational in 1962, and therefore, after

1962, all flows below Hartwell were regulated. Since the effects of system operation were to be investigated, outflows regulated by at-site requirements at Hartwell could not be used in the analysis.

STREAMFLOW AND EVAPORATION DATA. The routing interval selected for the operational simulation was 24 hours. Average daily discharge data were obtained from streamflow gage records on the Savannah River, using the U.S.G.S. WATSTORE data retrieval system. The three gaging stations used were U.S.G.S. Numbers 012187 at Iva, SC. (near Hartwell), 021890 at Calhoun Falls, S.C. (near the Russell damsite), and 021970 at Augusta, Ga. (below Clark Hill). The Iva gage furnished local inflows at Hartwell. In order to determine local inflows at Russell, flows at the Calhoun Falls gage were correlated to same and previous day flows at the Iva gage. The reason for multiple correlation was to account for lag time between gages. The correlation yielded an equation of the form:

$$\hat{Q}_2 \text{ Calhoun Falls} = C_1 Q_1 \text{ Iva} + C_2 Q_2 \text{ Iva} + C_3$$

where subscripts 2 and 1 denote same and previous days, respectively. Local inflows at Russell were then computed using the following relationship:

$$\hat{Q}\text{ local RBR} = \hat{Q}2\text{ Calhoun Falls} - \frac{C_1Q_1\text{ Iva} + C_2Q_2\text{ Iva}}{C_1 + C_2}$$

This yielded a statistically accurate set of local inflows such that:

$$\bar{Q}\text{ Calhoun Falls} = \bar{Q}\text{ Iva} + \bar{Q}\text{ local}$$

Inflows at Clark Hill after 1952 were obtained from plant operational records, and were similarly correlated with same and previous day flows at Iva. Because Clark Hill inflow records reflect reservoir evaporation, a few of the local inflows were computed to be negative, indicating days in which evaporation and other losses were greater than local inflow.

Average monthly evaporation values obtained from climatological records for the inflow period were used in the simulation. Net average monthly evaporation and pool elevation-surface area data are used in HEC-5C to compute evaporation losses for the routing interval selected. Evaporation computations were made for Hartwell and Russell, but not for Clark Hill due to previous inclusion of evaporation in computed local inflows. Net average monthly evaporation data were determined by subtracting average monthly precipitation from total average monthly evaporation.

RESERVOIR ELEVATIONS, AREAS, STORAGES AND CAPACITIES. These data were available from design memoranda from all three projects. Elevation-area-storage curves, tailwater rating curves, and spillway rating curves provided physical data required as input to HEC-5C. Tailwater rating curves and reservoir elevations, along with turbine efficiency data are required for computation of discharge-generating capacity-operating head relationships. Generating and pumping capacities can be limited by overload ratios. Pumping performance data were obtained for the pump turbines at Russell and used in HEC-5C to determine pumping capacities for headwater and tailwater conditions during pumping.

HYDROPOWER AND NAVIGATION REQUIREMENTS. At-site average monthly power requirements for Hartwell and Clark Hill were obtained from operational records, along with predicted requirements for Russell from previous hydropower studies for conventional power production. It was assumed for the purposes of the simulation that the plant factors at Russell with pumped storage would be the same as with the originally authorized conventional installation. This assumption was based upon recommendations of the Southeastern Power Administration. It was recognized that variation in pumping cycle durations can allow for variation in generating plant factor and greater marketing flexibility.[9] Monthly and daily plant factors were determined for

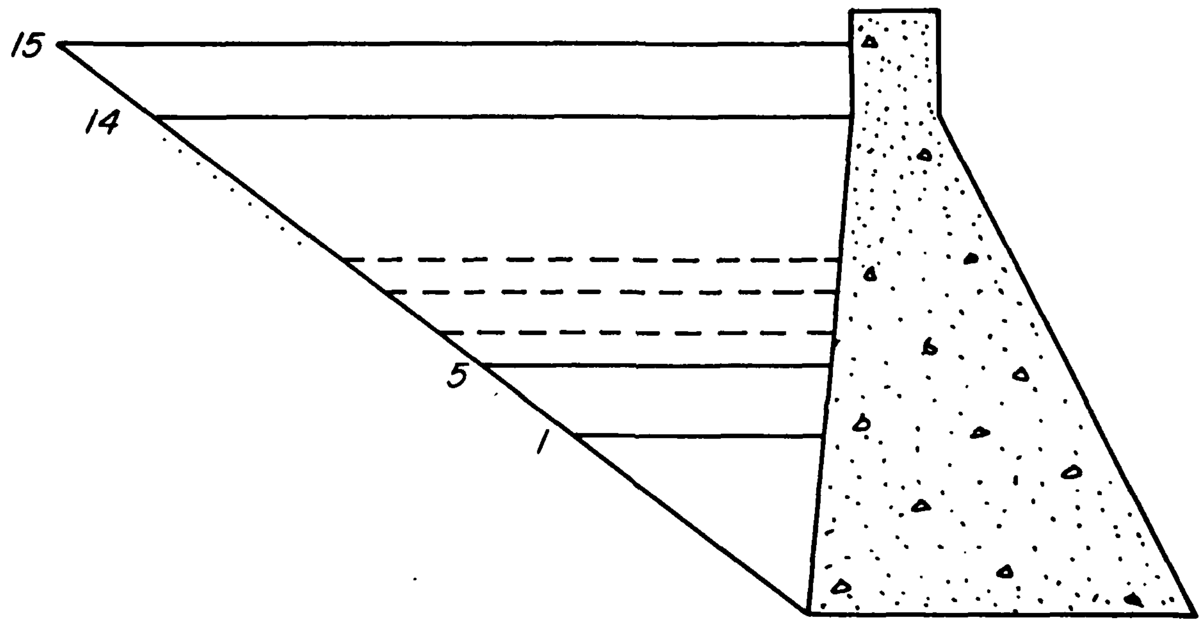
Hartwell, Clark Hill, and Richard B. Russell. Daily plant factors were expressed as percentages of total weekly power production which are in turn utilized in HEC-5C as percentages of total monthly power production. Daily plant factors at all three plants are used in the model to define duration of daily full-capacity generation at each plant when operating for system or at-site requirements. Generation at Hartwell and Russell is generally confined to 5 days per week, while it is desirable to maintain an average daily discharge of 6,300 cfs from Clark Hill for river navigation (control point 4 on Figure 2). The minimum average daily release required from Clark Hill is 5,800 cfs. Pumping plant factors for Richard B. Russell were determined by considering availability of pumping energy and time constraints on pumping. System monthly generation energy requirements were determined by summing monthly at-site requirements at Hartwell and Clark Hill along with expected at-site demands at Russell.

RESERVOIR STORAGE LEVELS. All three reservoirs were divided into levels, representing percentages of flood control, power and other project requirement storages. These levels are used in HEC-5C to define storage limits for various types of releases, and for determination of system storage balance. System storage balance is achieved when all projects are at the same level. For the three Savannah River plants, it is desirable that all three projects be in the same mode of operation simultaneously. For example, all projects should be in flood control operation or have equal percentages of power storage remaining

at any time. It was felt this type of operation would tend to minimize energy dumped, pumping energy used, and primary energy shortages. Reservoir levels defined by input can be varied from month to month, allowing for rule curve operation of reservoirs. This was the case for Hartwell and Clark Hill, whereas Russell's power storage and elevations do not vary seasonally. Table 1 defines reservoir level divisions shown in Figure 3.

Model Output and Simulation Results

OUTPUT OPTIONS UTILIZED. Some of the HEC-5C output options utilized in the Savannah River system simulations are shown in table 2. Two conditions were simulated for the three-plant system with pumped storage at Richard B. Russell. The first case simulated operations with at-site requirements of Russell equal to the expected at-site generation when operating in the system. The purpose of this simulation was to insure Russell was being fully utilized (even slightly overutilized) in predicting the most severe within-day pool fluctations that could be expected to occur at Russell and Clark Hill. The second case simulated operations of the three-plant system for system energy. Both simulations included at-site navigation release requirements at Clark Hill. An additional simulation of system operation without the pump turbines at Russell was performed. This case produced results for



RESERVOIR STORAGE LEVELS

FIGURE 3

TABLE 1
Reservoir Levels and Release Requirements

Level	Definition and Release Requirements
1	Top of inactive pool or minimum power pool; releases are made to pass inflow or minimum required release below this level, whichever is less.
5	Top of buffer; minimum required or primary power releases are made below this level.
6-14	Equal volumes of power storage within a reservoir; level 14 is maximum power pool and mimimum flood control pool; releases are made for primary power or minimum desired releases.
15	Top of flood control pool; primary and secondary energy releases with maximum flow constraints are made to return pool to maximum power pool. All inflows are released above level 15.

TABLE 2

Output Options Utilized

Output by Routing Interval (Summaries)						
Output by Reservoir or Control Point				System Output		Summaries
Flow Data	Level Data	Case Data	Energy Data	Level Data	Energy Data	
Inflow (1,2,3,4) Outflow (1,2,3,4) Diversion (1,2,3,4) Pumping Discharge (1,2,3,4)	Elevation (2,3,4,6,7) Storage Level (2,3,4)	Basis for Release Control Point for which release is made	Energy generated (1,2,3,4,8) Capacity (2,3,4,6)		Energy Generated (1,2,3,4,8) Energy Shortage (1,2,3,4,8)	1. Sum 2. Minimum 3. Maximum 4. Mean 5. Yearly Sum 6. Yearly Minimum 7. Yearly Maximum 8. Yearly Mean
Summary Output Only						
			Primary Energy Generated (1) Secondary Energy Generated (1) Pumping Energy Required (1,8)	System Storage (2,3)	Primary Energy Generated (1) Secondary Energy Generated (1) Pumping Energy Required (1,8)	

comparison with system operation with pumped storage. Tables 3, 4, and 5 show simulation results of power production for these three conditions.

In addition to output described in table 2, daily pool elevations and within day pool fluctuations at each reservoir were written to a scratch file for statistical analysis. A utility program was developed to compile cumulative density distributions for these data by reservoir. Mean, standard deviation, and skew data for the distributions are shown in table 6.

SENSITIVITY ANALYSIS. Sensitivity tests during model development were performed to evaluate differences in energy production and pool fluctuations due to operation of three-plant system with at-site requirements at Russell from energy production due to pure system operation. Operation for system energy was found to significantly reduce dump energy, primary energy shortages, and pumping energy from operation with at-site requirements. This is evident from data shown in tables 3 and 4. Additional benefits of system operation were the reduction of average within-day pool fluctuations at Russell and Clark Hill, and a better balance of reservoir storage levels.

Sensitivity tests to evaluate the effect of adjusting system energy requirements were also conducted, producing significant changes in reservoir drawdown and primary energy shortages. It was

TABLE 3

System Energy With At-site Requirements at Richard B. Russell

	Average Capacity (MW)	Avg Annual Energy Required (GWH)	Avg Annual Energy Generated (GWH)	Avg Annual Primary Shortage (GWH)	Avg Annual Dump Energy (GWH)	Avg Annual Pumping Energy (GWH)
Hartwell	295.00	-	425.842	-	-	-
Richard B. Russell	635.865	775.698	753.404	-	-	547.306
Clark Hill	304.857	-	586.789	-	-	-
Total System	1,236.322	1,483.955	1,766.035	94.659	376.758	547.306

TABLE 4

System Energy

	Average Capacity (MW)	Avg Annual Energy Required (GWH)	Avg Annual Energy Generated (GWH)	Avg Annual Primary Shortage (GWH)	Avg Annual Dump Energy (GWH)	Avg Annual Pumping Energy (GWH)
Hartwell	293.990	-	425.612	-	-	-
Richard B. Russell	636.426	-	708.648	-	-	472.704
Clark HIll	304.647	-	589.413	-	-	-
Total System	1,235.063	1,483.955	1,723.672	86.385	326.102	472.704

TABLE 5

System Energy Without Pumped Storage at Richard B. Russell

System Energy

	Average Capacity (MW)	Avg Annual Energy Required (GWH)	Avg Annual Energy Generated (GWH)	Avg Annual Primary Shortage (GWH)	Avg Annual Dump Energy (GWH)	Avg Annual Pumping Energy (GWH)
Hartwell	291.409	-	-	-	-	-
Richard B. Russell	318.913	-	-	-	-	-
Clark Hill	304.551	-	-	-	-	-
Total System	914.873	1,094.177	1,423.611	69.905	399.339	-

TABLE 6

RESERVOIR POOL ELEVATION AND FLUCTUATION DATA

CASE	RESERVOIR: HARTWELL		RICHARD B. RUSSELL		CLARK HILL	
	Elevation,x (feet msl)	Fluctuation,y (feet)	Elevation,x (feet msl)	Fluctuation,y (feet)	Elevation,x (feet msl)	Fluctuation,y (feet)
1. Pumped storage operation at-site requirements at Russell	$\bar{x}$ = 656.77 σ_x = 2.9763 g_x = -1.9328	$\bar{y}$ = 0.1139 σ_y = 0.0795 g_y = 1.9001	$\bar{x}$ = 472.10 σ_x = 1.9851 g_x = 0.0154	$\bar{y}$ = 0.4778 σ_y = 0.2086 g_y = -0.3429	$\bar{x}$ = 325.80 σ_x = 3.5698 g_x = -0.7761	$\bar{y}$ = 0.1672 σ_y = 0.0738 g_y = 0.7744
2. Pumped storage operation without at-site requirements at Russell	$\bar{x}$ = 655.66 σ_x = 3.6775 g_x = -1.3768	$\bar{y}$ = 0.1274 σ_y = 0.0865 g_y = 1.7868	$\bar{x}$ = 472.54 σ_x = 1.9852 g_x = -0.0564	$\bar{y}$ = 0.4213 σ_y = 0.2455 g_y = 0.2111	$\bar{x}$ = 325.73 σ_x = 3.3660 g_x = -0.7059	$\bar{y}$ = 0.1514 σ_y = 0.0801 g_y = 0.4534
3. Conventional operation without at-site requirements at Russell	$\bar{x}$ = 655.12 σ_x = 5.5142 g_x = -2.4149	$\bar{y}$ = 0.1207 σ_y = 0.0800 g_y = 1.5081	$\bar{x}$ = 472.73 σ_x = 2.0122 g_x = 0.0492	$\bar{y}$ = 0.0455 σ_y = 0.0742 g_y = 3.8172	$\bar{x}$ = 325.33 σ_x = 3.7356 g_x = -0.8251	$\bar{y}$ = 0.1051 σ_y = 0.0634 g_y = 1.6599

found that monthly system energy requirements could not be lowered below a certain minimum level without causing an imbalance in reservoir storage levels. When energy requirements were too low, power releases through the system were too low to support downstream navigation requirements, causing Clark Hill to make up the difference and subsequently drawing down relative to Hartwell and Russell. When high at-site requirements were placed on Richard B. Russell, both Russell and Clark Hill were found to draw down relative to Hartwell, due to excessive generating and pumping at Russell.

Conclusions and Recommendations for Further Study

The operational simulation and statistical summaries produced sufficient information to satisfy many objectives of the pumped-storage feasibility study. In addition, some of the information furnished by the operational simulation is expected to be useful in future studies.

The methodology developed in this investigation is expected to provide the basis for real-time regulation of the Savannah River system when the Richard B. Russell project is brought on-line.

The simulation results yielded evidence that system operation is more efficient than operation for at-site requirements, producing less dump energy, pumping energy, and primary energy shortages. In addition, system operation was simulated to reduce pool fluctuations

and achieve a better balance of reservoir storage levels than operation with at-site requirements.

Since the routing period included the period of maximum drawdown for the system, and primary energy shortages were simulated to be very small relative to total energy requirements, system capacity at plant factors specified for the simulation was considered reliable, although the simulation was not performed to determine system reliability. Plant factors were largely based on operational records, and therefore the simulation was felt to be realistic in terms of system reliability. It can be noted from data presented in Tables 4 and 5 that the ratio of primary energy shortage to system demand with pumped storage is approximately 10 percent smaller than for system operation without pumped storage. This indicates that the addition of pumped storage could provide somewhat greater flexibility in meeting system requirements.

Further study would be useful to develop methods for achieving optimal operational economy within the constraints of project requirements for pumped storage systems. Although there have been a number of optimization studies for operation of reservoir systems, none have been applied to pumped-storage systems for maximization of recreation, water supply, navigation, generation capacity, and primary energy benefits minus pumping costs. Additional refinements will be

incorporated into HEC-5C for allocation of reservoir storage releases, although optimization routines are not presently planned.

Acknowledgments

This study was authorized under the Savannah River Basin Study, approved 5 May 1966 by the Committee on Public Works, House of Representatives. The study was conducted by the Savannah District Corps of Engineers, with programming development and assistance being provided by the Hydrologic Engineering Center, Corps of Engineers.

Appendix I - References

1. Thompson, Major H. Jr., "Wallace Dam," Paper 9259, Journal of the Power Division, Proceedings of A.S.C.E., Vol. 98, No. PO2, October, 1972, pp. 333-348.

2. North Pacific Division, Corps of Engineers, Power Pondage Studies, Mid-1980 Conditions, Report CRT-30, December 1976.

3. North Pacific Division, Corps of Engineers, Water Surface Fluctuation Studies, Mid-1980 Conditions, Report CRT-31, January 1977.

4. North Pacific Division, Corps of Engineers, Pumped-Storage in the Pacific Northwest, an Inventory, Report 26, January 1976.

5. O'Brien, Eugene, Freeman, Clarence N. and Dixon, John H., "Water and Power in the Northeast," Journal of the Power Division, A.S.C.E., Vol. 102, No. PO2, Proc Paper 12574, November 1976, pp. 195-208.

6. Sigvaldson, O. T., "A Simulation Model for Operating a Multiple Purpose Reservoir System," Water Resources Research, Vol. 12, No. 2, April 1976, pp. 263-278.

7. Jackson, Reiner, "Reservoir Operation for Recreation Usability;" Paper 10058, Journal of the Hydraulics Division. Proceedings of A.S.C.E., Vol. 99, No HY10, October 1973, pp. 1813-1822.

8. Hydrologic Engineering Center, Corps of Engineers, HEC-5C, Simulation of Flood Control and Conservation System, Users Manual, March 1976.

9. Savannah District, Corps of Engineers, Trotters Shoals Dam and Reservoir, General Design Memorandum, Supplement No. 1, Recommendation for Inclusion of Pumped Storage, December 1969.

APPENDIX II - NOTATION

The following symbols are used in this paper:

C_i	=	Constants of regression
GWH	=	Gigawatt hours (10^9 watt hours)
g_x	=	Skew coefficient of pool elevations
g_y	=	Skew coefficient of pool fluctuations
MW	=	Megawatts (10^6 watts)
Q	=	Daily discharge
$\bar{Q}$	=	Average of daily discharges
$\hat{Q}$	=	Least squares estimator of daily discharge
$\bar{X}$	=	Average pool elevation, feet mean sea level
$\bar{Y}$	=	Average daily pool fluctuation in feet
σ_x	=	Standard deviation of pool elevations.
σ_y	=	Standard deviation of pool fluctuations.